IMPROVED TIMEKEEPING USING ADVANCED TRAPPED-ION CLOCKS

R. L. Tjoelker, J. D. Prestage, and L. Maleki
Jet Propulsion Laboratory, MS298-100
4800 Oak Grove Dr., Pasadena, CA 91109, USA

Abstract

Timekeeping requires practical, continuously operating frequency standards with exceptional long-term stability. JPL mercury linear ion trap standards (LITS) operate continuously with short-term stability to $2.0 \times 10^{-14}/\tau^{1/2}$ and long-term stability limited by remaining sensitivity to the second-order Doppler shift, which varies with ion number fluctuations. In this paper, we report measurements in a 12-pole trap showing a greater than twenty-fold sensitivity reduction to all parameters affecting the Second-Order Doppler Shift. This advance should further improve practical ground-based ion standard stability to the 1×10^{-16} level and allow significant engineering simplifications enabling small, high performance flight standards.

INTRODUCTION

Continuous, reliable operation is required in most practical applications of high performance atomic frequency standards. National timekeeping and the generation of timescales are typically accomplished with ensembles of continuously operating hydrogen maser and commercial cesium clocks. Ultra-stable standards are also required for VLBI radio astronomy and for deep space navigation via ranging and Doppler spacecraft tracking. Terrestrial navigation made possible by, for example, the Global Positioning System (GPS) is based on continuously operating atomic clocks on earth-orbiting satellites. These clocks must also be small and low power in addition to being insensitive to large environmental perturbations.

Practical linear ion trap-based mercury ion standards with no lasers, microwave cavities, or cryogenics have been developed by JPL for radio science applications in NASA's Deep Space Network (DSN) and for timekeeping applications at the US Naval Observatory [1,2,3]. These standards operate continuously with a measured short-term stability as low as $2 \times 10^{-14}/\tau^{1/2}$. The flicker floor has typically been limited to about 7×10^{-16} at 100,000 seconds with measured long-term drifts as low as 1×10^{-16}/day [4]. The stability limitation results from the relatively large remaining second-order Doppler shift and the instability of this offset over long averaging times. This instability originates with fluctuations in ion number and consequential ion temperature fluctuations resulting from ion heating that occurs off axis in a quadrupole linear trap. In typical operation, the ion number is not directly stabilized, though measured frequency stability below 10^{-15} (total second-order Doppler shift of 2×10^{-12}) indicates the ion cloud of approximately 10^7 ions is typically stable over days to better than 0.1%. With large ion clouds small variations in the ion number can lead to significant changes in the average temperature of the ion cloud even in the presence of a helium buffer gas. As a result, the achievable frequency stability is coupled to the stability of all parameters affecting the ion load and loss rates. This includes the stability of trap potentials, electron emission to ionize neutral mercury, as well as all

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **DEC 1999**	2. REPORT TYPE	3. DATES COVERED **00-00-1999 to 00-00-1999**
4. TITLE AND SUBTITLE **Improved Timekeeping Using Advanced Trapped-Ion Clocks**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Jet Propulsion Laboratory,MS298-100,4800 Oak Grove Dr,Pasadena,CA,91109**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001481. 31st Annual Precise Time and Time Interval (PTTI) Planning Meeting, 7-9 December 1999, Dana Point, CA

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

gas pressures (mercury, helium, and background) which are also affected by vacuum pump speed and vacuum chamber wall temperature.

In this paper we present initial measurements performed with a 12-pole multipole trap configuration which show a dramatic reduction in sensitivity to all parameters affecting the second-order Doppler shift. The use of a multipole trap for ion storage in atomic clock applications has only recently been discussed [6]. Higher pole traps have been used elsewhere to study ion-molecule low energy collisions and reactions [5] and octopole rf electrodes have found many uses for transporting ions from one location to another.

LINEAR ION TRAP STANDARDS (LITS) DEVELOPMENT AND APPLICATIONS

Linear Ion Trap Standards (LITS) using the 40.5 GHz microwave transition in ^{199}Hg ions confined in a four-rod ion trap and optically pumped with a UV discharge lamp have been under development for several years. At JPL this development is currently focussed on three applications with differing goals. The LITS standards were originally developed for applications in the NASA Deep Space Network where the performance of highest interest is in the 1-10,000 second range. Very high stability is required for radio science experiments and as a stable reference for a two way Ka-band Doppler link currently being developed with the Cassini Spacecraft in route to Saturn. The Signal-to-Noise Ratio (SNR), and atomic line Q achieved in trapped-ion standards can be very high, with stability of $2\times10^{-14}/\tau^{1/2}$ demonstrated [2,7]. The delivered performance depends on the local oscillator and operation with a Cryogenic Sapphire Oscillator (CSO) provides significant improvements over use of a hydrogen maser, or quartz crystal oscillator [7].

Timekeeping activities require continuous operation with very high long-term stability for averaging times >10,000 seconds. Mercury is less sensitive to most perturbations than hydrogen, rubidium, and cesium and the achievable long-term performance in LITS quadrupole standards relies on keeping the large 2nd-order Doppler shift stable over days and months. Long-term stability is further improved by operating with smaller ion clouds, but at the expense of signal to noise and short-term stability.

Another application being addressed is the need for high performance atomic standards in a spaceflight environment. In flight standards, size, mass, power, mechanical, magnetic, and radiation sensitivity are major constraints in addition to performance and reliability. One of the most challenging flight applications is operation on board a GPS NAVSTAR type satellite, where each new generation requires increased operation lifetime and performance. The LITS technology is amenable to this application, though there exist unique technological challenges to preserve the highest performance in a small, robust instrument. It was the need for a smaller LITS which, in part, led to the development of a dual region trap configuration [8]. This configuration, referred to as an extended Linear Ion Trap (LITE), takes advantage of the fact that ions can be easily moved between specialized regions by DC fields. Th LITE is particularly advantageous in reducing the size of the magnetic shields and passively provides improvement in long-term stability without compromising the large SNR previously achieved in the LITS.

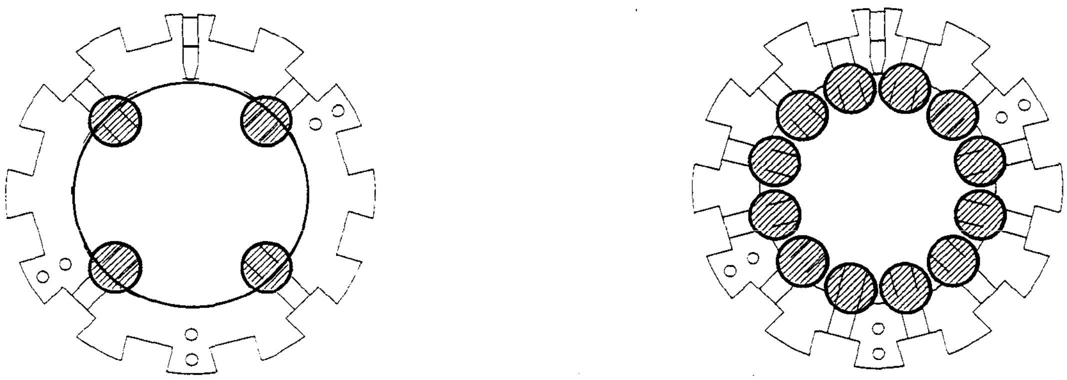
RECENT RESEARCH DEVELOPMENTS

Two new recent research developments should further improve operability of the LITS technology and impact all three development efforts described. The first is the use of alternative buffer gases that would allow for simplifications of the vacuum pumping configuration. The second is the use of a multipole ion trap to reduce rf heating effects.

NITROGEN BUFFER GAS

LITS mercury standards typically use a helium buffer gas (10^{-5} mbar) to collision-cool the ions to near room temperature and increase loading efficiency. The need for this high helium pressure constrains vacuum pump selection. Although ion and getter pump combinations have been used with mercury, their non-constant pumping speed leads to frequency drifts, presumably through consequential variations in the large second-order Doppler shift. For this reason we typically operate with mechanical pump systems, providing a nearly constant pump speed over the operational pump life, but limiting continuous operation to service intervals of less than two years.

We have studied alternative buffer gasses and molecular nitrogen has shown promise as a replacement for helium [9]. Nitrogen has an advantage over helium in that it is effectively pumped by ion & getter pump technology providing a sealed, lower power vacuum system than currently in operation. Early measurements indicate a frequency pulling verse pressure turnover near $2x10^{-7}$ mbar. At this nitrogen pressure achieving 10-year ion pump life is straightforward. Preliminary operation with nitrogen buffer gas shows a reduction in signal to noise by a factor of 2 and an additional negative frequency shift. This likely indicates that collisional cooling is less effective and that the resulting equilibrium ion temperature is higher than achieved with helium. Since the second-order Doppler shift is larger, sensitivity to variations in all parameters affecting the shift are also larger. A LITS standard has operated for 6 weeks with nitrogen and an ion pump, and good long-term stability achieved. The use of nitrogen should be even more effective when rf heating from the ion trapping fields is reduced.



(a) (b)

Figure 1: (a) Cross-section of the quadrupole linear ion trap used for loading and optically pumping approximately 10^7 mercury ions and (b) cross-section of the 12-pole ion trap used for ion confinement during the 40.5 GHz microwave interrogation.

MULTIPOLE TRAPPED ION STANDARDS

For large ion clouds in a quadrupole linear ion trap, most of the motional energy is stored in the micromotion necessary to generate the force to balance the space charge repulsion. For a typical cloud, buffer gas cooled to 500 K, the 2nd-Doppler shift from rf micromotion can be up to 3 times the secular motion contribution to the energy [10,6]. In a multipole trap configuration (Figure 1b) the ions are only weakly bound with confining fields that are effectively zero through the trap interior and grow rapidly near the trap potential walls. Because the ions in a multi-pole rf trap spend relatively little time in the region of high rf electric fields, there is very little rf heating.

With large ion clouds where space-charge effects are non-negligible, the total second-order Doppler shift for the trapped ions in a multipole trap is [6]

$$\frac{\Delta f}{f} = -\frac{3k_B T}{2mc^2}(1 + \frac{2}{3}N_d^{\,k})$$

N_d^k describes the total micromotion contribution to the 2^{nd}-order Doppler shift and is computed from evaluating the micromotion averaged across the ion cloud:

$$N_d^{\,k} = \frac{\int n(r) r F_d^{\,k}(r) dr}{\int n(r) r dr}.$$

n(r) is the density profile of the ions in thermal equilibrium at temperature T, and F_d^k represents a function describing the averaged micromotion normalized to the averaged thermal motion [6]. In the limit of small ion clouds, where space charge effects are negligible, $N_d^k = 1/(k-1)$, where 2k is the number of poles. Therefore, in the linear quadrupole trap with a small number of non-interacting ions, $N_d^{k=2} = 1$. This is a consequence of the equality of the average secular energy and average micromotion energy in a harmonic (quadrupole) trap. (As space charge interaction grows larger, $N_d = N_d^{k=2}$ increases and can be as large as 3 for large buffer gas-cooled Hg ion clocks). A 12-pole trap by contrast begins (in the small cloud limit) as $N_d^{k=6} = 1/5$, already 5 times smaller than the quadrupole. Because the field-free interior volume of the multi-pole is much larger than the quadrupole with the same radius, the low-density limit is satisfied with a much larger number of ions.

OPERATION OF THE MULTI-POLE LINEAR TRAP STANDARD

We have recently fabricated a 12-pole trap coupled to a co-linear quadrupole trap. Ion loading and optical pumping occurs in the "open" quadrupole trap, as in the traditional LITS, and microwave interrogation is performed in the 12-pole region. Both traps are driven at 1 MHz, though for stable operation the effective quadrupole well depth is ≈3 eV and the 12-pole well depth ≈0.3 eV. Fluorescence measurements demonstrate negligible ion loss in both the 12-pole region and during transport across the junction between the two traps.

For typical clock operation approximately 10^7 ions are transferred back and forth every 10 seconds. The ion density in the 12-pole is much less than inside the quadrupole (The 12-pole region is 3.8 times longer than the loading trap and the effective diameter of the ion cloud increases from about 1.5 mm to 9 mm.) After ions are loaded and optically pumped in the quadrupole, they are electrically transferred and microwave interrogation is carried out in the multipole region with a 6-second Rabi pulse. The ions are then electrically transferred back andfluorescence observed. The peak atomic resonance signal size observed is approximately 50,000 counts/second with a background stray light level of approximately 220,000 counts/second. With these parameters the predicted short-term Allan deviation (limited by photon-counting statistics) is $7\times10^{-14}/\tau^{1/2}$ $[\mathrm{Hz}^{-1/2}]$.

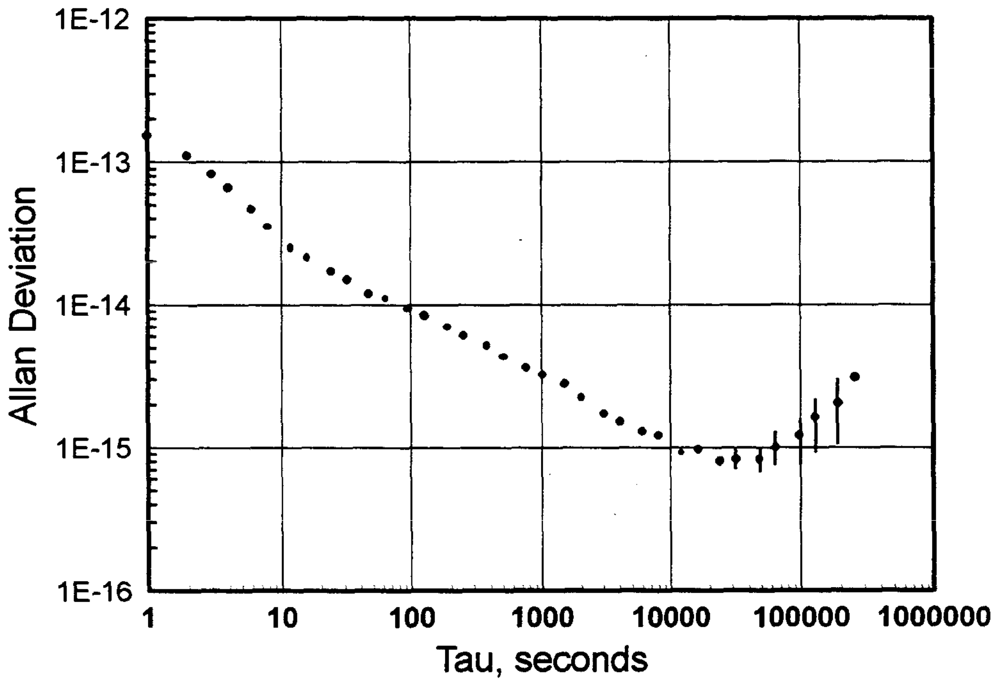


Figure 2: The Allan Deviation of the multi-pole trapped ion standard verse a SAO hydrogen maser.
The slope of $1\times10^{-13}/\tau^{1/2}$ is expected as a result of using a H-maser as the local oscillator. The stability beyond 30,000 seconds is limited by the reference H-maser.

FREQUENCY STABILITY MEASUREMENTS

Figure 2 shows the LITE 12-pole clock stability using a hydrogen maser as the local oscillator and measured against an available reference hydrogen maser with no cavity compensation (SAO-26). The measured slope of $1\times10^{-13}/\tau^{1/2}$ is degraded from the theoretical Allan deviation because of the limited stability of the LO hydrogen maser. The long-term drift observed beyond 30,000 seconds in this 7-day continuous measurement of the 12-pole stability is characteristic drift in the H-maser. Measured ambient environment thermal fluctuations indicate an unregulated thermal sensitivity of less than 2×10^{-15}/deg C. This unregulated sensitivity is at least 10-20 less sensitive than in previous LITS standards and 10,000 less sensitive than in a typical hydrogen maser. A second LITE 12-pole will soon be operational and will allow much lower noise floor measurements.

DOPPLER SHIFT MEASUREMENTS

The leading frequency offsets for LITS have been published elsewhere [11]. Changes in these offsets will lead to frequency instabilities over time. It is well known that the second order Doppler shift has been the largest source of potential frequency instabilities in Hg frequency standards. To achieve a high SNR, traditional LITS Hg standards typically operate with a second-order Doppler frequency offset, which grows as large as 2×10^{-12} as the quadrupole linear trap is filled.

The measured frequency pulling of the 40.5 GHz mercury clock transition in the 12-pole trap as a function of

ion number is shown in Figure 3. The observed fluorescence(proportional to ion number) increases as the endpin dc potential is raised as shown in Figure 4. In contrast to the $2x10^{-12}$ shift observed in the traditional LITS from empty to full, the multipole trap shows a reduced frequency pulling by at least a factor of 20. A reduction of a factor of 5 is expected from the multipole trap due to geometric considerations alone (the calculation is performed assuming constant ion temperature). The factor of 20 improvement suggests that the ion cloud is heated much less in the multipole trap for large ion clouds than in the quadrupole trap. This factor of 20 reduced sensitivity also explains the reduced sensitivity to external variations in the ambient temperature previously observed. We should expect a similar sensitivity reduction on all operating parameters that couple through the 2^{nd}-order Doppler shift, including sensitivity to all pressure regulation, trap potential stability, electron emitter stability, and pumping speed.

Since the multi-pole linear trap has reduced the rf heating of the ion cloud to such a large degree, we anticipate $1x10^{-16}$ stability floors should be attainable. This could occur with the same electronics and degree of regulation as currently exist in the LITS. The ability to achieve very high long-term stability with modest regulation requirements should allow for significant engineering simplifications in spaceflight standards that require exceedingly long operational life. We are currently developing a prototype standard of approximately 20 kg and 50 watts and the multipole trap enables a small vacuum system (approx 2 cm x 20 cm), which should maintain high stability and very low drift. The reduced rf heating should also preserve high performance using a sealed ion pump with a nitrogen buffer gas.

Though not developed for primary frequency standard applications, it may soon be practical to have clock accuracy approaching 10^{-14} in a rack-mountable Hg clock using the multipole linear trap. With the reduced sensitivity, and much smaller second-order Doppler offset due to ion micromotion, a 10^{-14} accuracy measurement would require a measurement of the secular temperature to 5% and a measurement of the helium buffer gas pressure shift to 10%. The ion cloud temperature can be measured by propagating microwaves along the axis of the linear 12-pole in a fashion previously demonstrated [12].

SUMMARY

High performance mercury trapped-ion standards with large ion clouds and optically pumped by an rf discharge lamp provide significant practical advantages, since they contain no lasers, cryogenics, or precise cavities. Recent advances in trapped-ion research should enable small, extremely high stability, and even high accuracy LITS-type standards for commercial or spaceflight applications. Although superior performance has been demonstrated for averaging intervals less than one day, the long-term stability obtained in a quadrupole linear ion trap has been limited by the remaining second-order Doppler shift. Initial measurements with a multipole ion trap show a greater than twenty-fold reduction in this shift. This should lead to a corresponding improvement in long-term stability and allow engineering simplifications which could have a significant impact in ground-and space-based timing applications.

ACKNOWLEDGMENTS

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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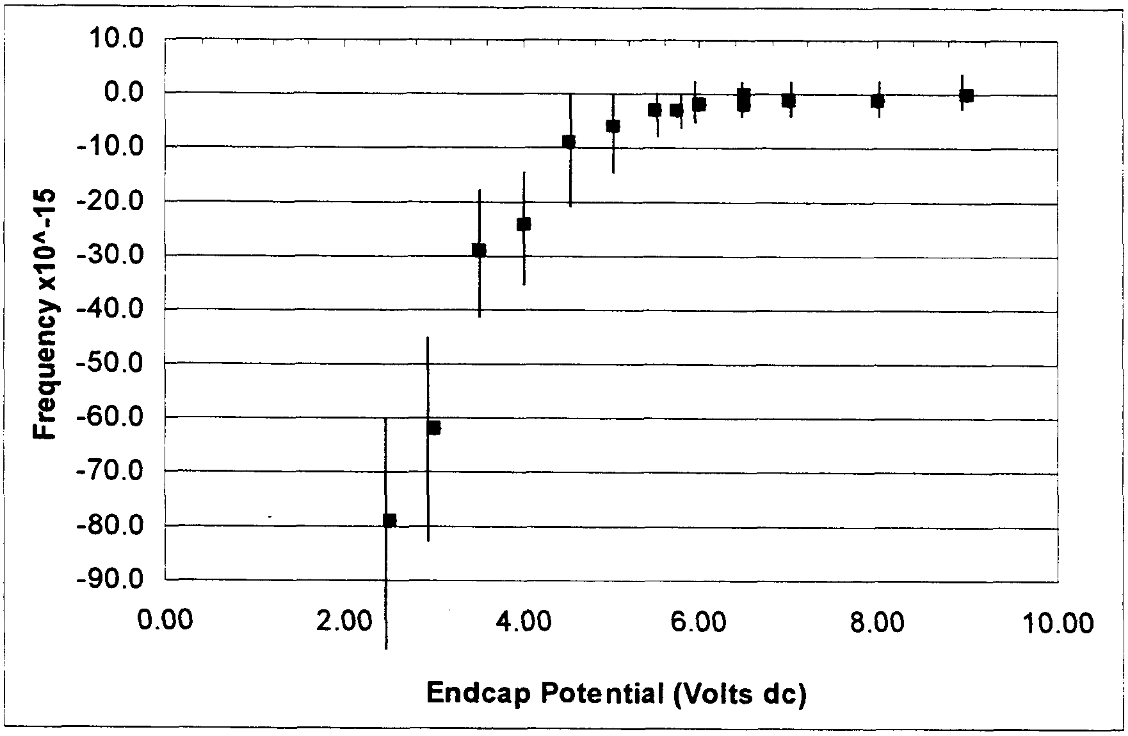

Figure 3: Second-Order Doppler frequency pulling as a function of ion number. The ion number is varied by changes in the endcap potential. This shift is twenty times less than observed with a similar number of ions in the traditional quadrupole linear ion trap.

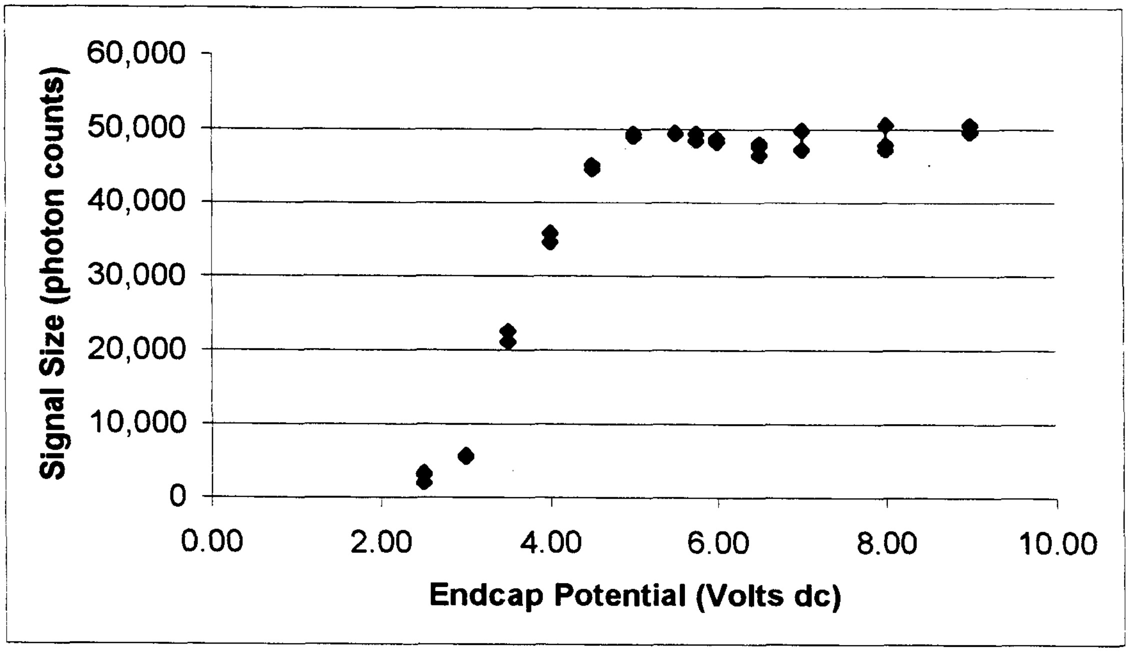

Figure 4: Fluorescence representing the 40.5 GHz atomic microwave transition proportional to the number of ions confined in the multipole trap. The ion number was varied to examine the 2nd Order Doppler offset and sensitivity to changes as a function of cloud size.